Wall-Modeled Large Eddy Simulation of Separated Flows

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JOHNS HOPKINS
WHITING SCHOOL
of ENGINEERING

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
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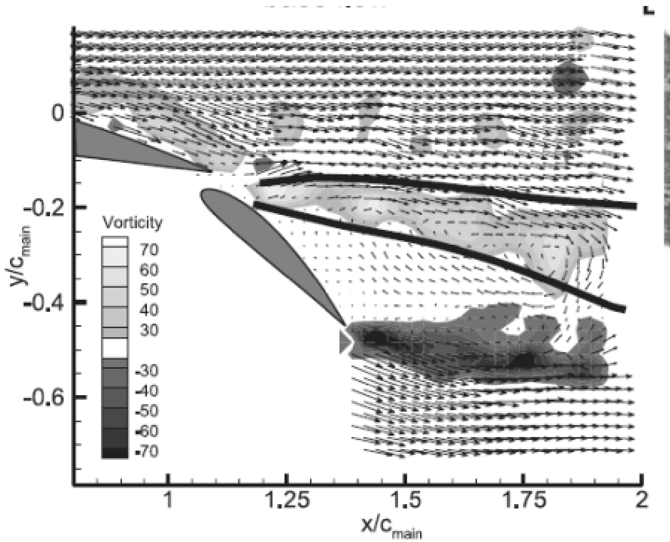
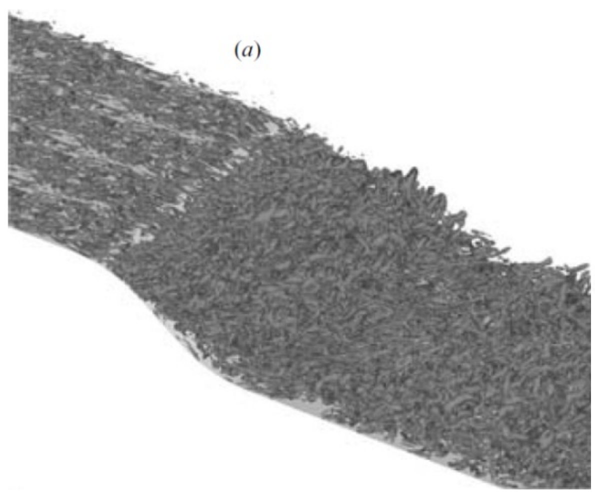
Motivation

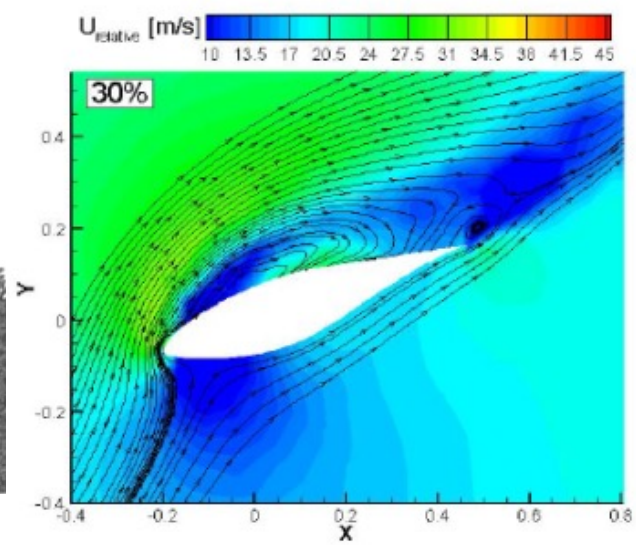
- Unsteady separated flows and recirculation regions occur on airfoils and blades for a wide range of Reynolds numbers from $O(10^4)$ to $O(10^6)$



Flow over airfoil with flap [1]



Flow through diffuser [2]



Flow over wind turbine blade [3]

[1] Petz, R., & Nitsche, W. (2007). Active separation control on the flap of a two-dimensional generic high-lift configuration. *Journal of Aircraft*, *44*(3), 865-874.

[2] Dandois, J., Garnier, E., & Sagaut, P. (2007). Numerical simulation of active separation control by a synthetic jet. *Journal of Fluid Mechanics*, 574, 25-58.

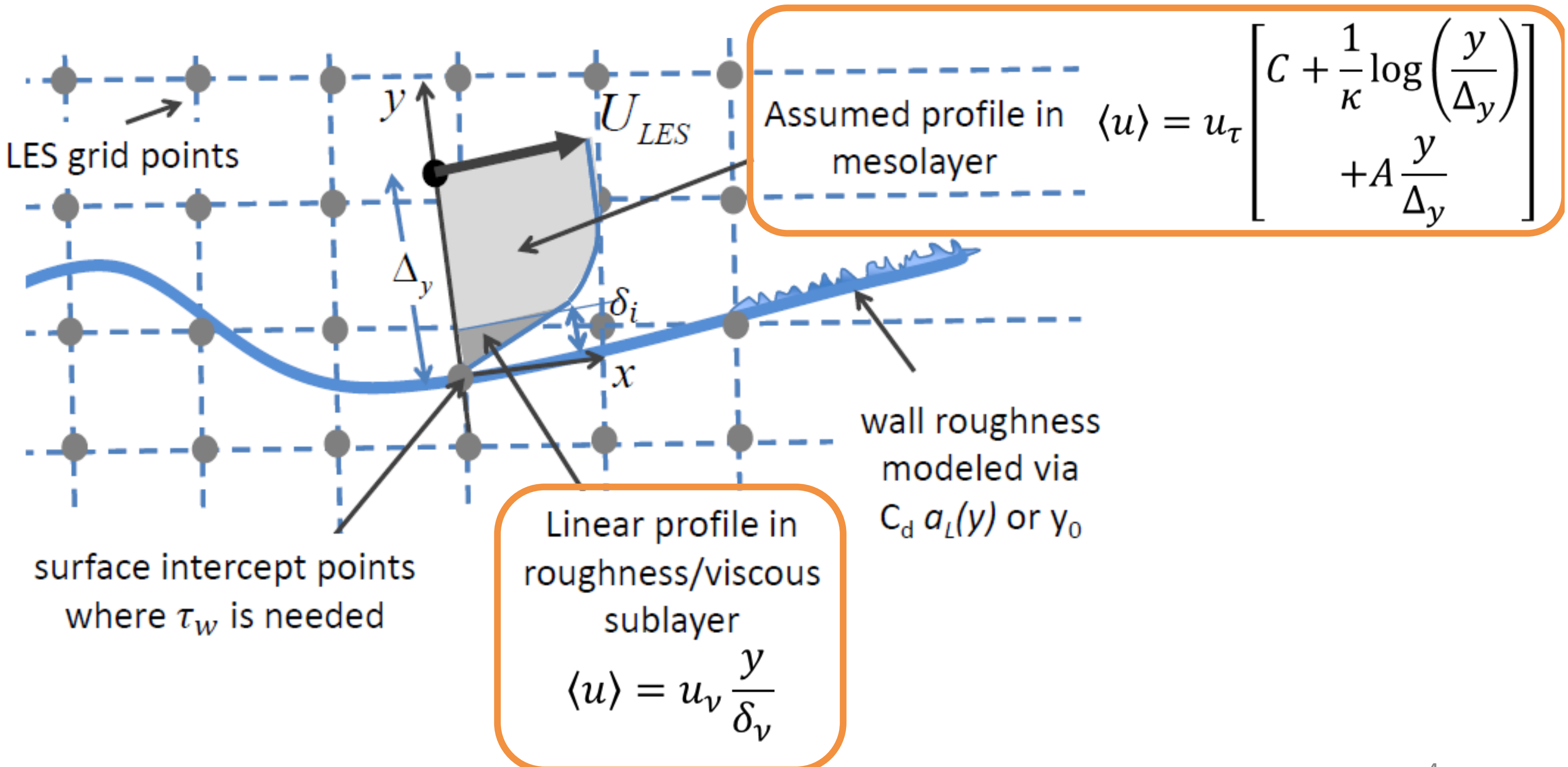
[3] Sezer-Uzol, N., & Long, L. N. (2006). 3-D time-accurate CFD simulations of wind turbine rotor flow fields. 44th AIAA Aerospace Sciences Meeting and Exhibit, January 2006, Reno, Nevada.

Research Goals

- Create predictive simulation tool for unsteady separated flows that is:
  - High-fidelity, turbulence-resolving
  - Tractable for high Reynolds number flows
- To enable:
  - Optimization of wing, blade, flap design
  - Rapid testing of active flow control strategies
  - Acoustic noise predictions at flight conditions

Integral Wall Model (iWMLES)

Use von-Karman-Paulhausen's integral method:
Assume velocity profile & integrate BL eqn analytically



Integral Wall Model (iWMLES)

Solve for 6 parameters to satisfy 6 constraints (for x):

1, 2) Velocity Continuity: $\langle u\rangle\left(y=\Delta_y\right)=U_{LES} \rightarrow u_\tau(C+A)=U_{LES}$

$$\langle u\rangle(y=\delta_i^+)=\langle u\rangle(y=\delta_i^-)\rightarrow u_\nu \frac{\delta_i}{\delta_\nu}=u_\tau\left[C+\frac{1}{\kappa}\log\frac{\delta_i}{\Delta_y}+A\frac{\delta_i}{\Delta_y}\right]$$

3) Inner Layer Height: $\delta_i=\min\left[\max\left(k, 11\frac{\nu}{u_\tau}\right),\Delta_y\right]$

4) Inner Length Scale: $\delta_\nu=\frac{1}{u_\nu}\left(\nu+\nu_{\tau,y=0}\right)$

5) Wall shear stress: $\tau_w=u_\tau^2=u_\nu^2+\int_0^k C_d a_L\langle u\rangle^2 dy$

6) **Vertically Integrated Momentum Equation:**

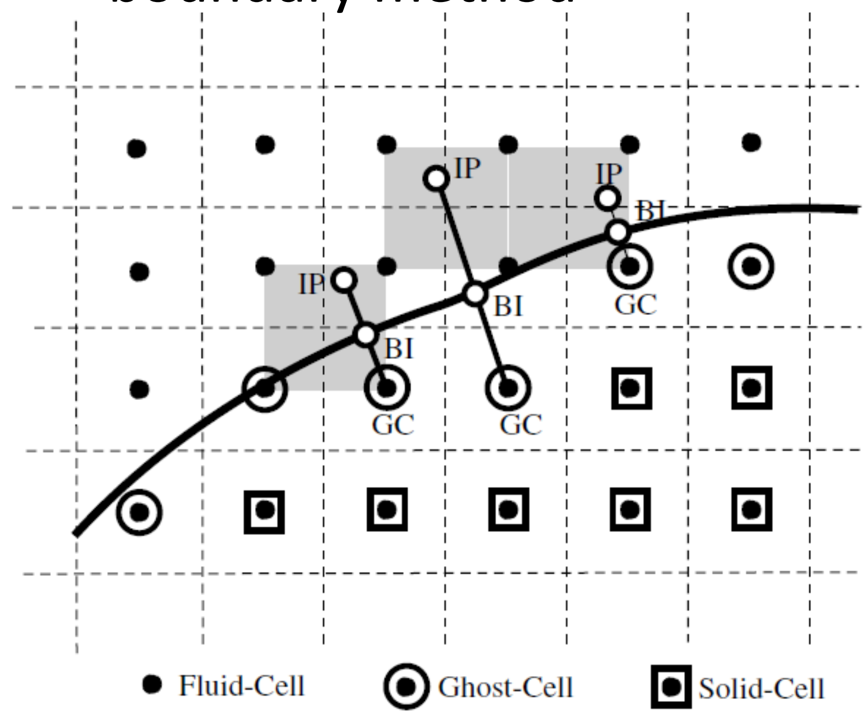
$$\frac{\partial}{\partial t}\int_0^{\Delta_y}\langle u\rangle \mathrm{dy}+\frac{\partial}{\partial x}\int_0^{\Delta_y}\langle u\rangle^2 \mathrm{dy}-U_{LES}\frac{\partial}{\partial x}\int_0^{\Delta_y}\langle u\rangle \mathrm{dy}+\frac{1}{\rho}\frac{\partial p}{\partial x}\Delta_y=(\nu+\nu_\tau)\frac{\partial\langle u\rangle}{\partial y}\Big|_{y=\Delta_y}-\tau_w$$

Evaluated Analytically

Numerical Methods

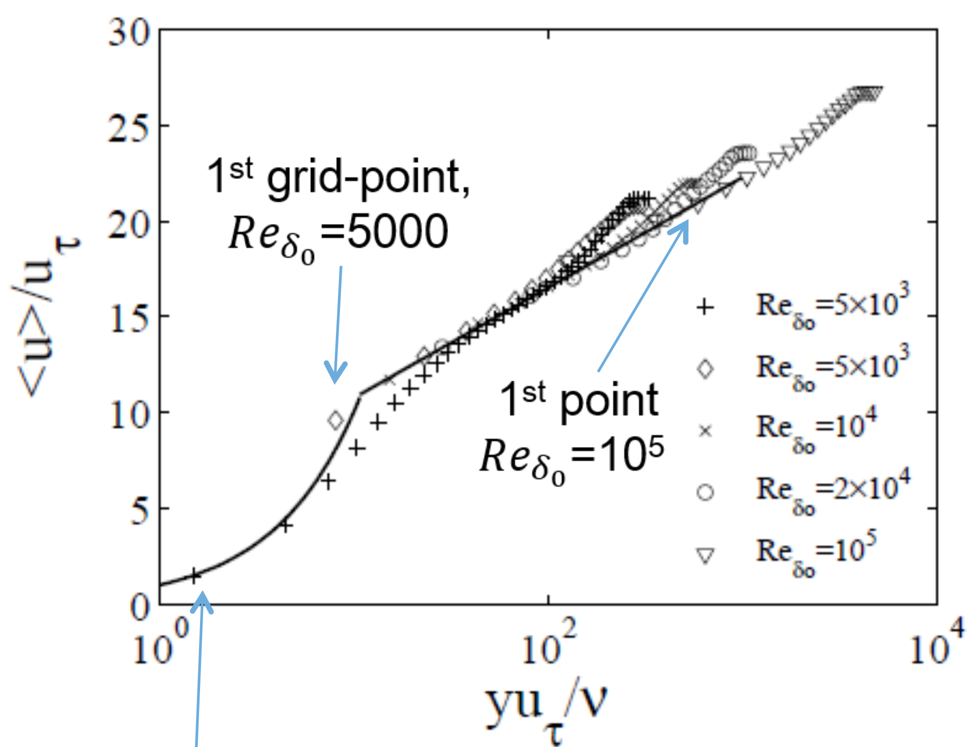
ViCar3D

- Cartesian finite difference: *2nd* order in space and time
- Dynamic Vreman model for subgrid-scale stress term in LES equations
- Recycle-rescale method of *Lund et al.* for developing turbulent boundary layer
- Sharp immersed boundary method

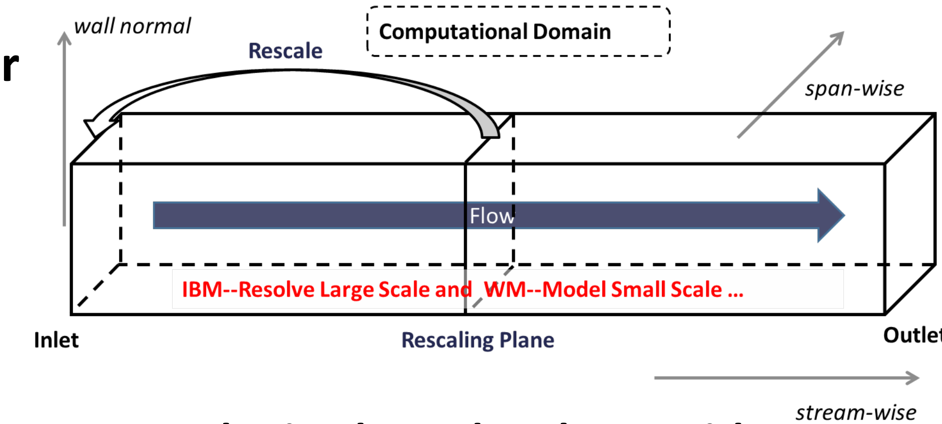


iWMLES Validation

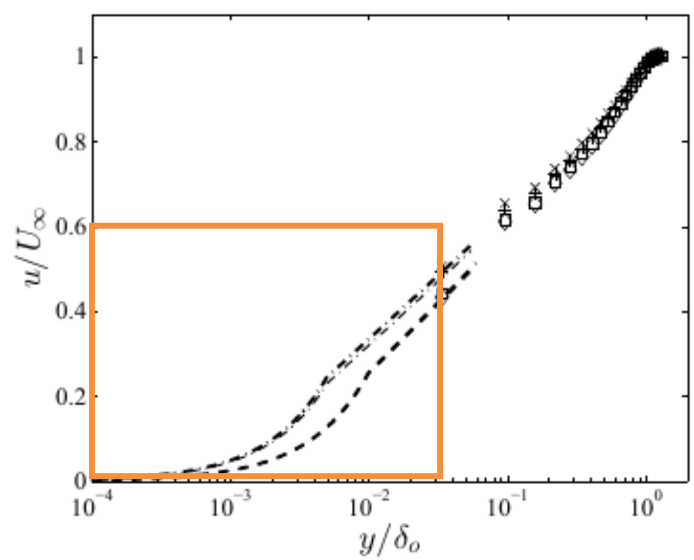
Flat plate developing boundary layer



1st grid-point, $Re_{\delta_0} = 5000$
("wall-resolving")



Developing boundary layer with unresolved surface roughness



- k=0.01, 0.005 for Re=2×10^5, 10^6 , y_0 = 0.0016, 0.00075;

Specific Objectives

- Demonstrate that iWMLES can predict turbulent separation and reattachment
  - turbulent separation bubble over a flat plate
- Validate integral Wall Model (iWMLES) for separated flows at high Re against wall-resolved LES
  - Create benchmark wall-resolved LES
  - For the same grid except near wall, compare Cf, Cp

Setup: Turbulent Separation Bubble

Flow over flat plate with suction boundary condition

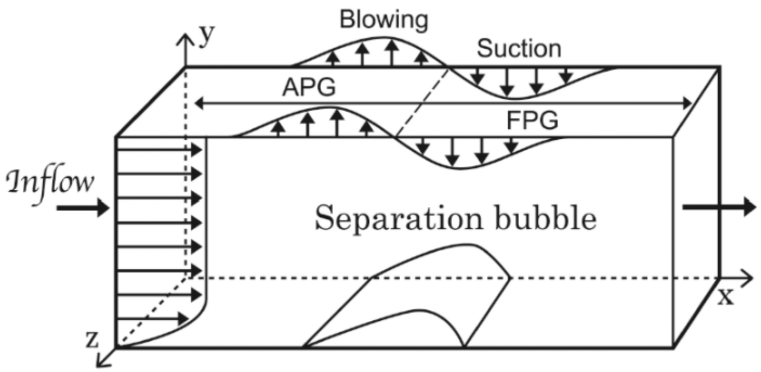


FIGURE 1. Computational domain.

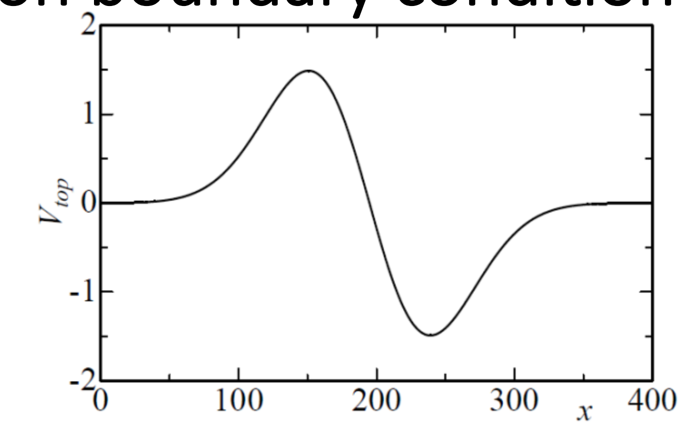


FIGURE 2. Transpiration velocity profile.

$Re_{\theta_0} = 985, Re_\tau = 353$

Domain size: 475 x 120 x 32 θ_0

Resolution: 512 x 192 x 96

Recycle Rescale plane at x = $75\theta_0$

No vorticity BC

Suction Profile:

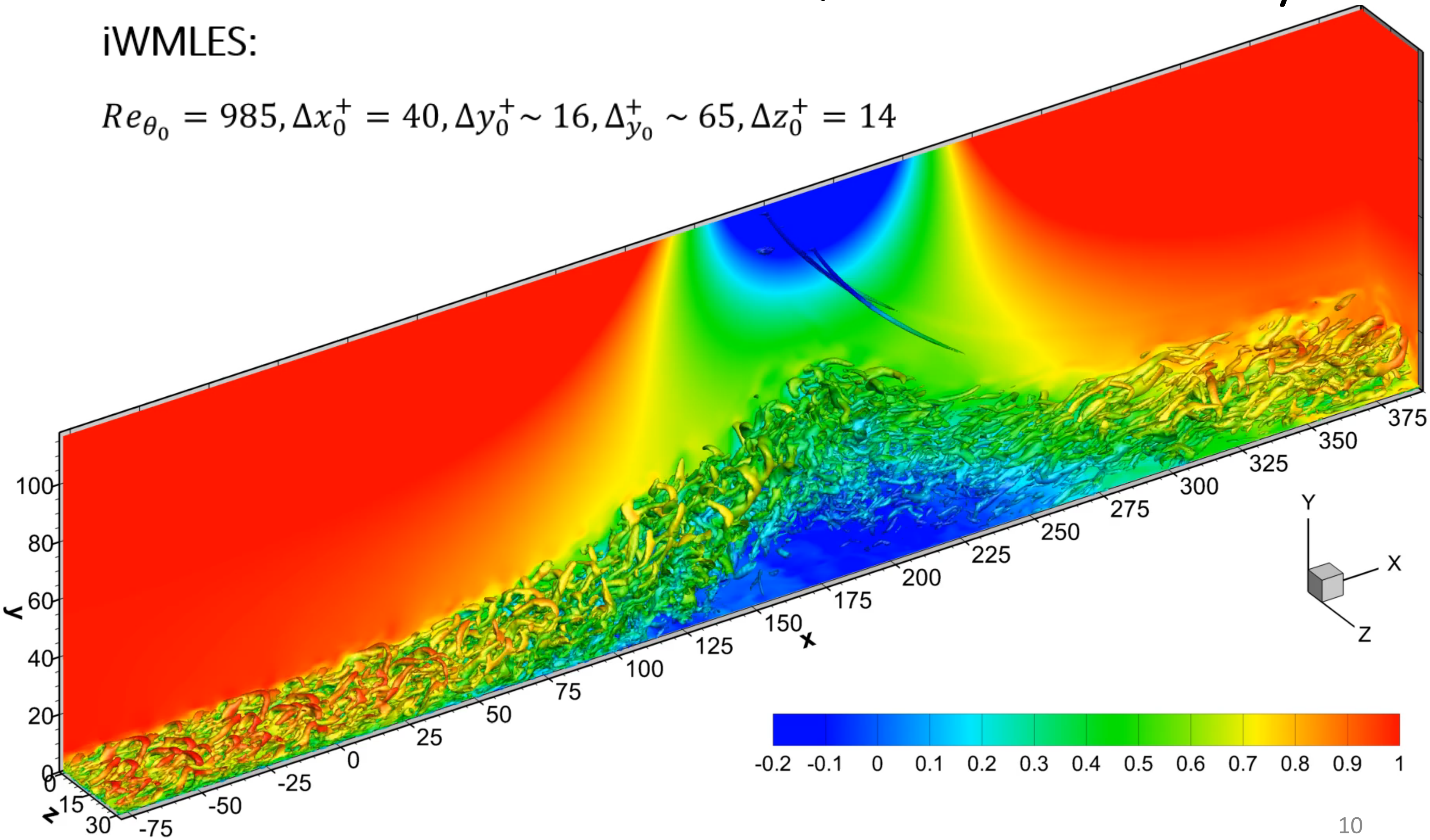
$V_m = 1.5U_0$

$L = 400\theta_0$, $x_c = 198\theta_0$

Abe, H., Mizobuchi, Y., Matsuo, Y., & Spalart, P. (2012). DNS and modeling of a turbulent boundary layer with separation and reattachment over a range of Reynolds numbers. *Center for Turbulence Research Annual Research Briefs*, *143*.

Results: Turbulent Separation Bubble

Instantaneous iso-surfaces of Q-criterion colored by U



Results: Turbulent Separation Bubble

Mean U Velocity

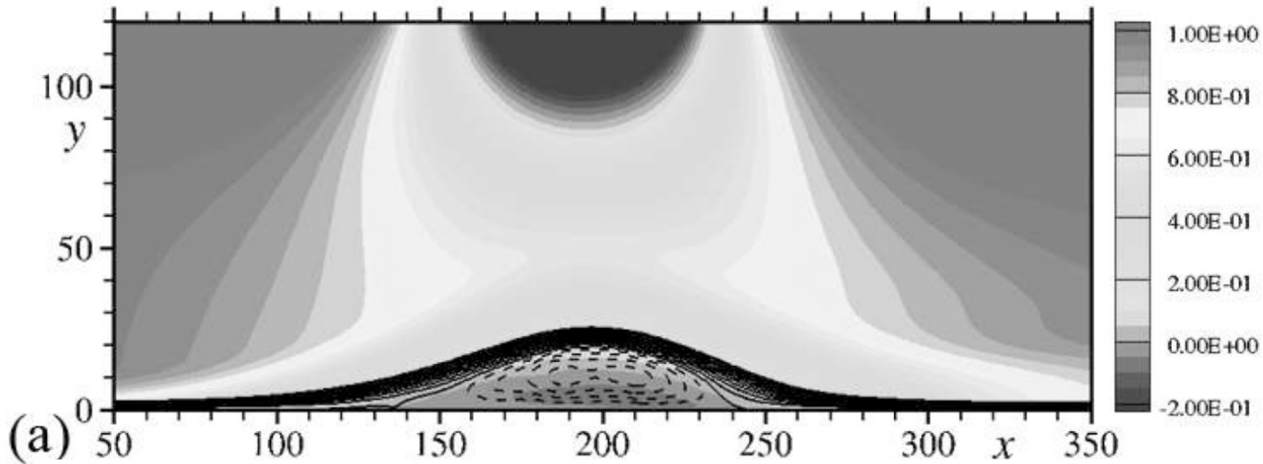
DNS*

$Re_{\theta_0} = 300$

$\Delta x_0^+ = 12.4$

$\Delta y_0^+ = 0.13$

$\Delta z_0^+ = 4.95$



iWMLES

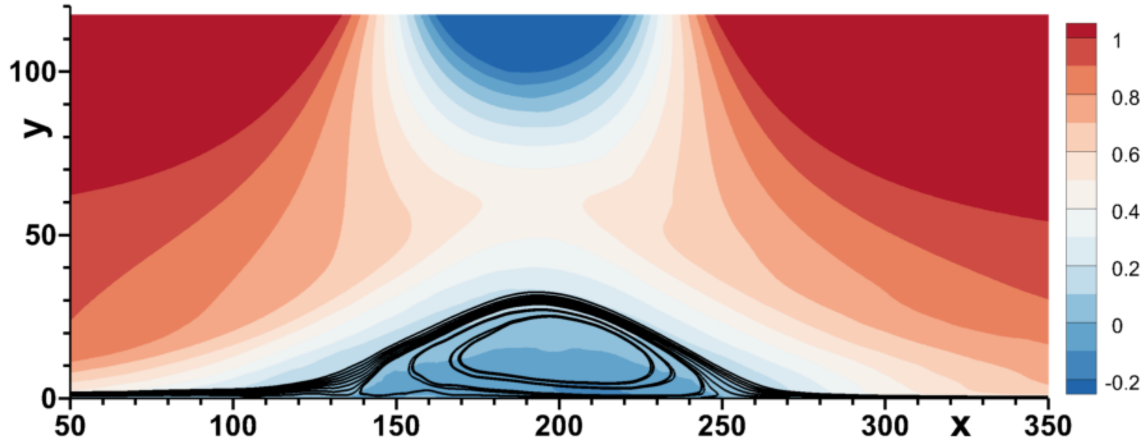
$Re_{\theta_0} = 985$

$\Delta x_0^+ = 40$

$\Delta y_0^+ \sim 16$

$\Delta_{y_0}^+ \sim 65$

$\Delta z_0^+ = 14$



*Abe, H., Mizobuchi, Y., Matsuo, Y., & Spalart, P. (2012). DNS and modeling of a turbulent boundary layer with separation and reattachment over a range of Reynolds numbers. *Center for Turbulence Research Annual Research Briefs*, *143*.

Results: Turbulent Separation Bubble

Turbulent kinetic energy

DNS*

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iWMLES

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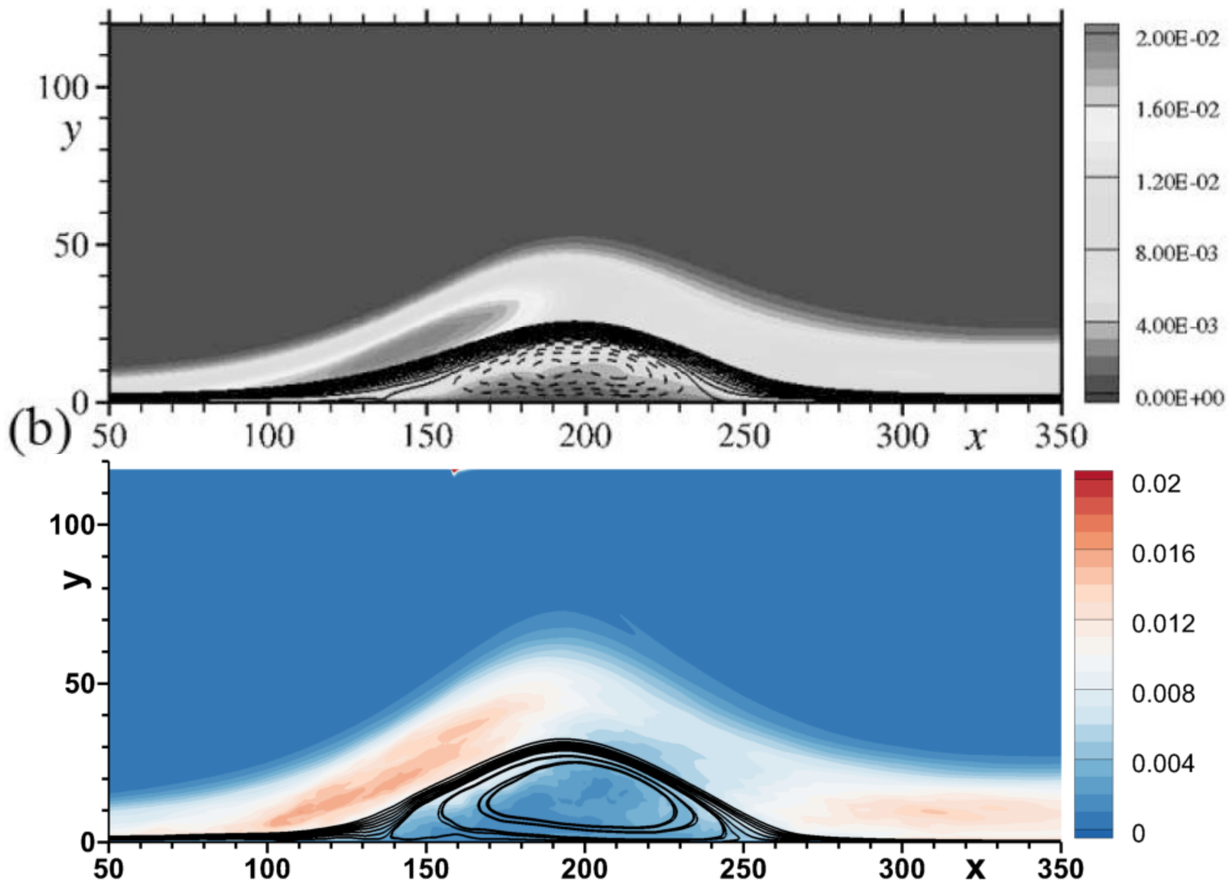

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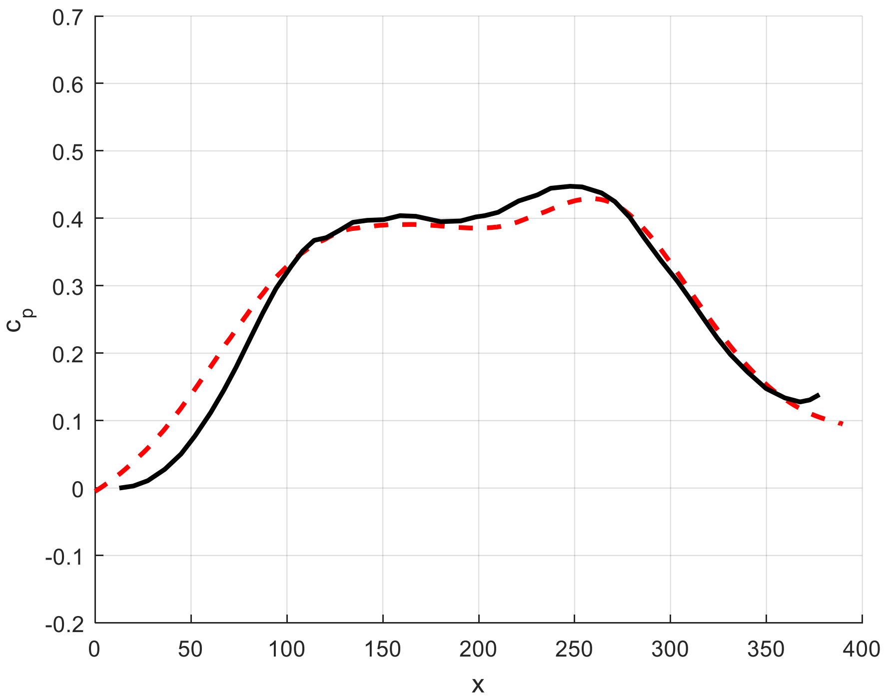
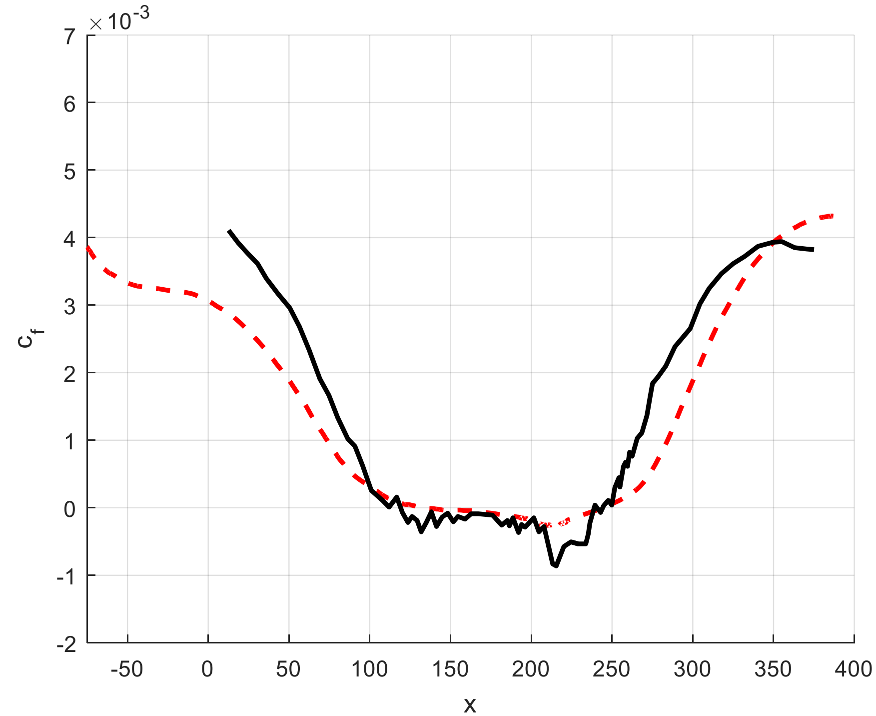
Results: Turbulent Separation Bubble

Coefficient of pressure



Coefficient of friction



DNS* (line) with $\Delta x_0^+ = 7.92,\ \Delta y_0^+ = 0.11,\ \Delta z_0^+ = 4.22$ and *3 billion* pts

iWMLES (dashes) with $\Delta x_0^+ = 40, \Delta y_0^+ \sim 16, \Delta_{y_0}^+ \sim 55, \Delta z_0^+ = 14$ and *9 million* pts

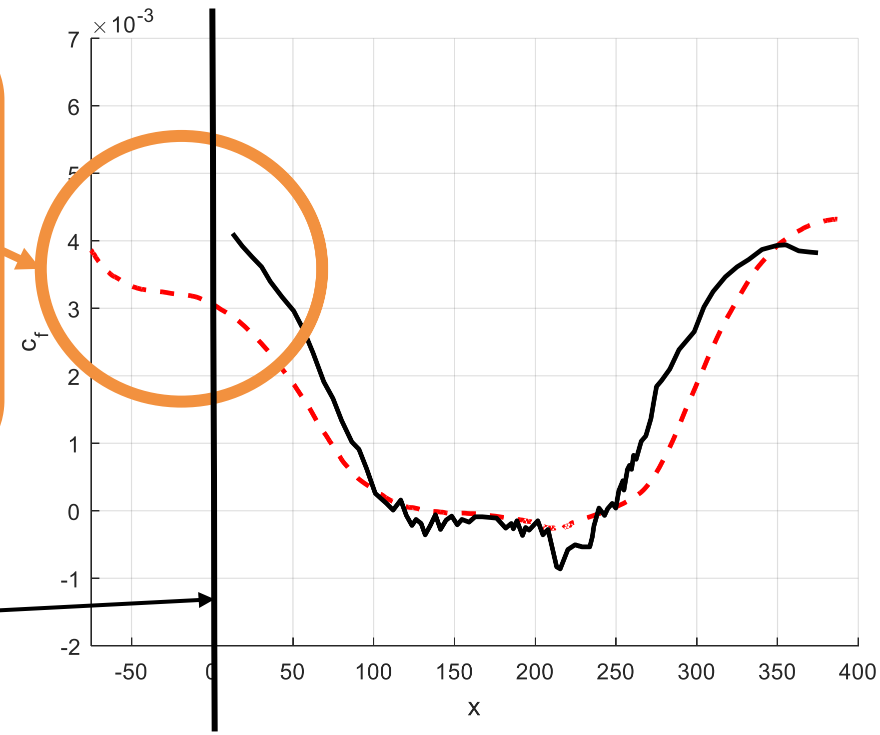
Abe, H., Mizobuchi, Y., Matsuo, Y., & Spalart, P. (2012). DNS and modeling of a turbulent boundary layer with separation and reattachment over a range of Reynolds numbers. *Center for Turbulence Research Annual Research Briefs*, *143*.

Results: Turbulent Separation Bubble

Coefficient of friction

Inlet friction velocity mismatch: effective Reynolds number from recycle-rescale method (*Lund et al*) in iWMLES is higher than DNS*

Recycle-rescale plane

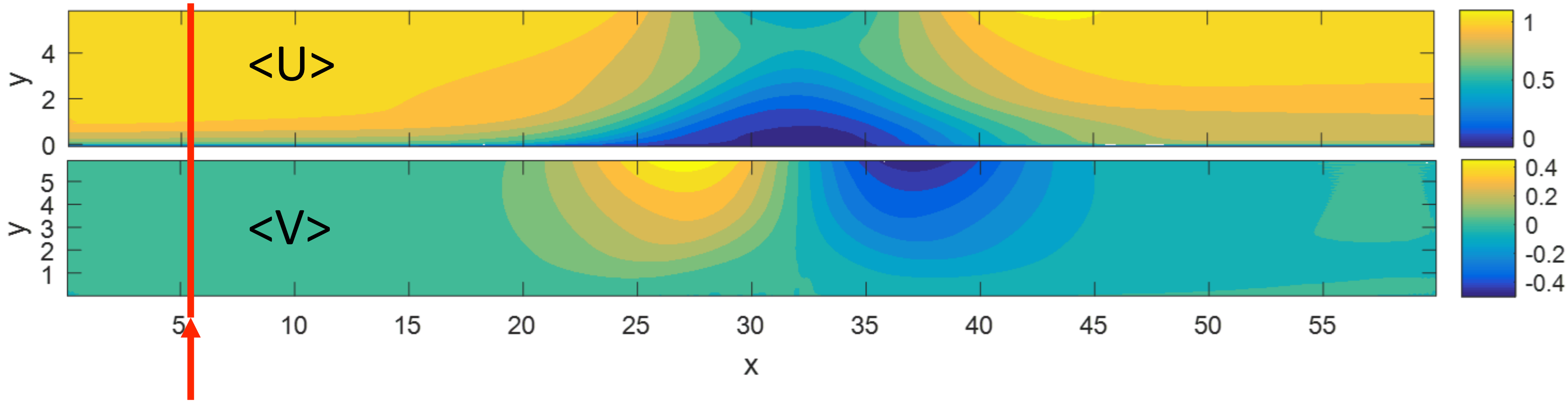


DNS (line), iWMLES (dashes)

*Abe, H., Mizobuchi, Y., Matsuo, Y., & Spalart, P. (2012). DNS and modeling of a turbulent boundary layer with separation and reattachment over a range of Reynolds numbers. *Center for Turbulence Research Annual Research Briefs, 143*.

Setup: Wall-resolved LES Benchmark

Flow over flat plate with suction boundary condition



Recycle Rescale plane at x = 6δ

$Re_\delta = 7703, Re_\tau = 353$

Domain size: 60 x 6 x 4 δ

Resolution: 512 x 128 x 96

No vorticity BC

Suction Profile:

$V_m = 0.5U_0$

$L = 45\delta$, $x_c = 32\delta$

Setup: Wall-resolved LES Benchmark

Wall-resolved LES vs iWMLES Resolution

	LES		iWMLES	
$N_x \times N_y \times N_z$	$512 \times 128 \times 96$		$512 \times 96 \times 96$	
$\Delta x/\delta, \quad \Delta x^+$	0.117,	44	0.117,	44
$\Delta z/\delta, \quad \Delta z^+$	0.042,	15	0.042,	15
$\Delta y/\delta, \quad \Delta y^+$	0.0014,	<1	0.0625,	16
$\Delta_y, \quad \Delta_y^+$		--	0.15,	$\sim$75

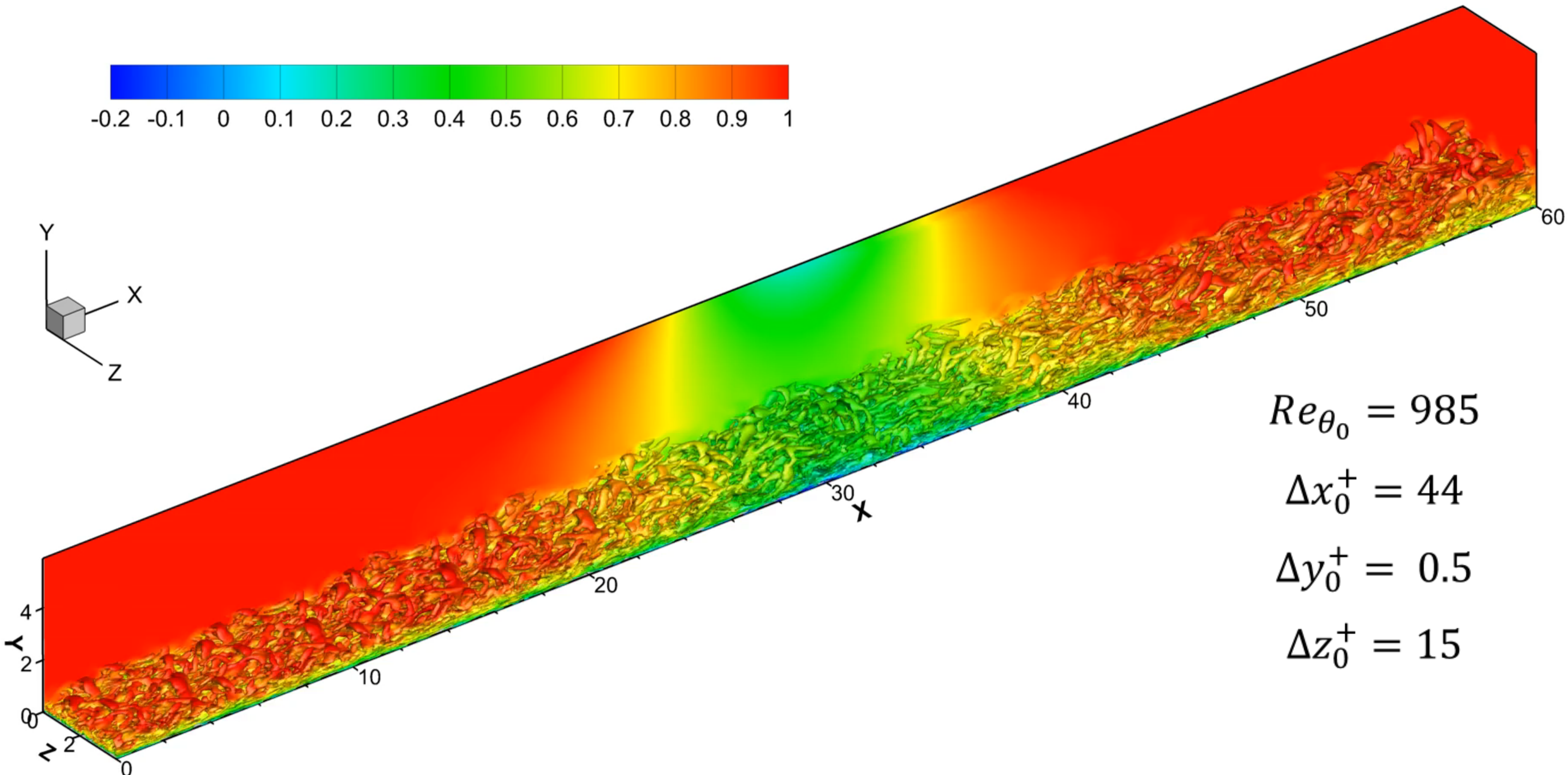
$\Delta_y \sim 3\,\Delta y(y=0)$ to avoid feeding the WM the LES under-resolution error in near-wall and to eliminate log-layer mismatch*

*Larsson, J. et al (2016). "Large eddy simulation with modeled wall-stress: recent progress and future directions", *Mechanical Engineering Reviews,* **3**:1.

Results: iWMLES vs Wall-resolved LES

Instantaneous iso-surfaces of Q-criterion colored by U

Wall-resolved LES, when suction is first turned on



$Re_{\theta_0} = 985$

$\Delta x_0^+ = 44$

$\Delta y_0^+ = 0.5$

$\Delta z_0^+ = 15$

Results: iWMLES vs Wall-resolved LES

Instantaneous iso-surfaces of Q-criterion colored by U

iWMLES, after separation bubble is well established

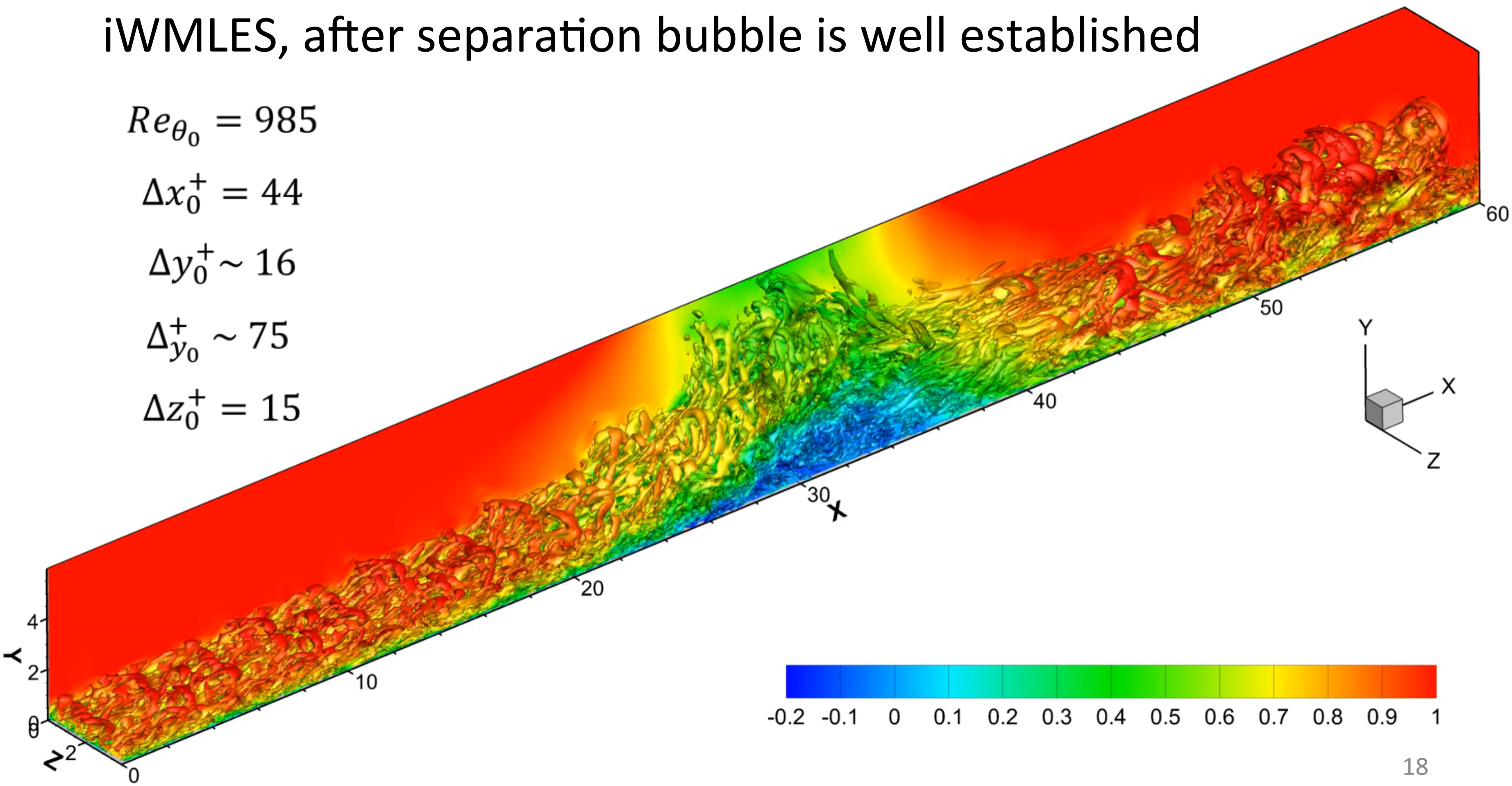
$Re_{\theta_0} = 985$

$\Delta x_0^+ = 44$

$\Delta y_0^+ \sim 16$

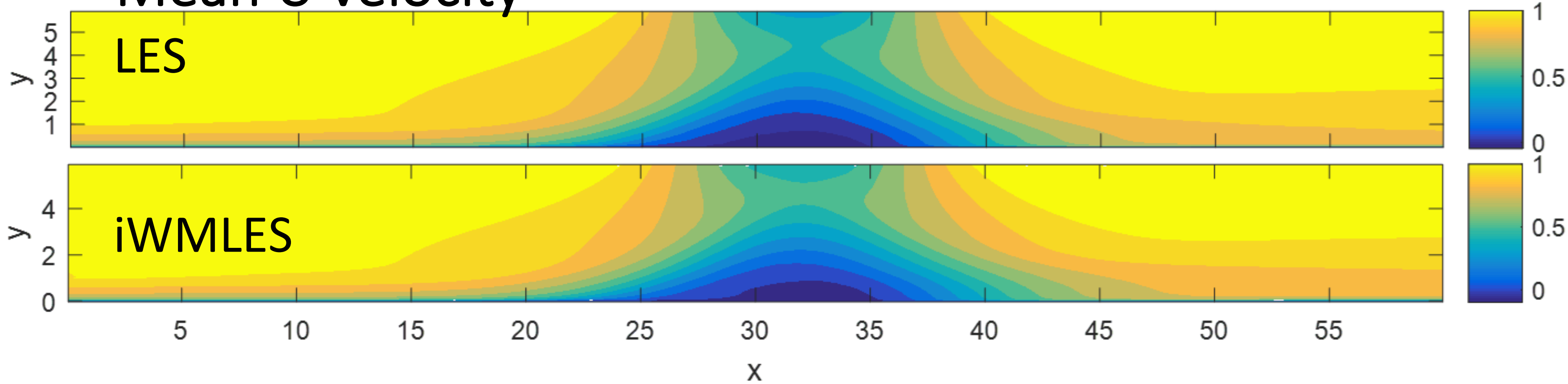
$\Delta_{y_0}^+ \sim 75$

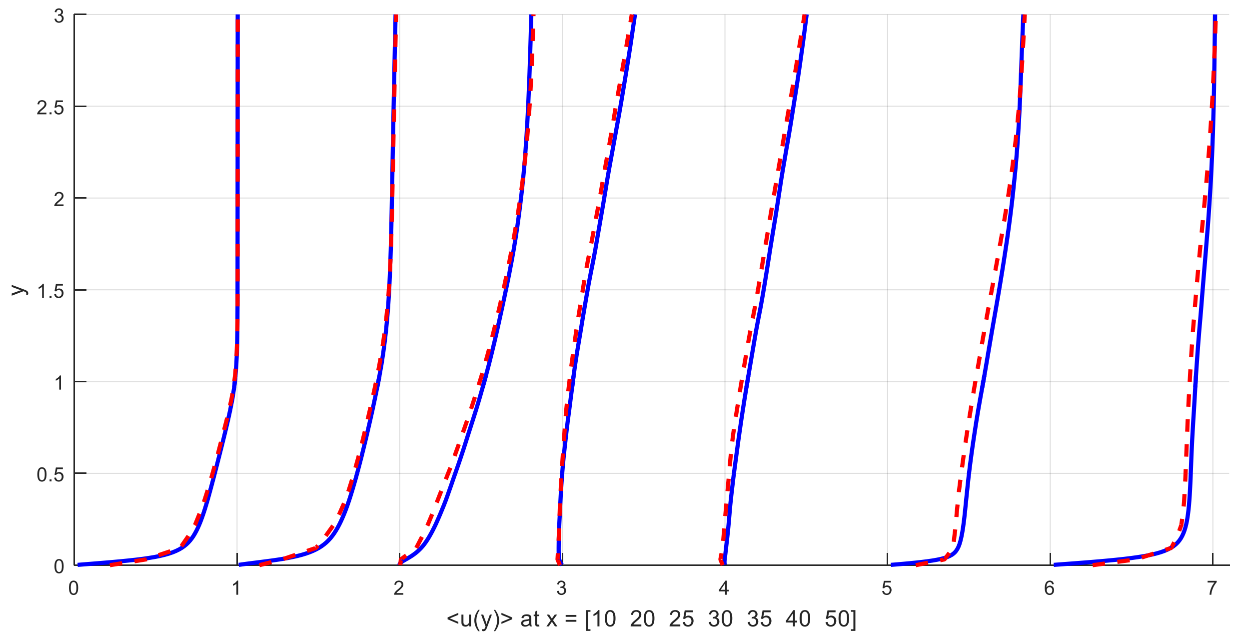
$\Delta z_0^+ = 15$



Results: iWMLES vs Wall-resolved LES

Mean U velocity

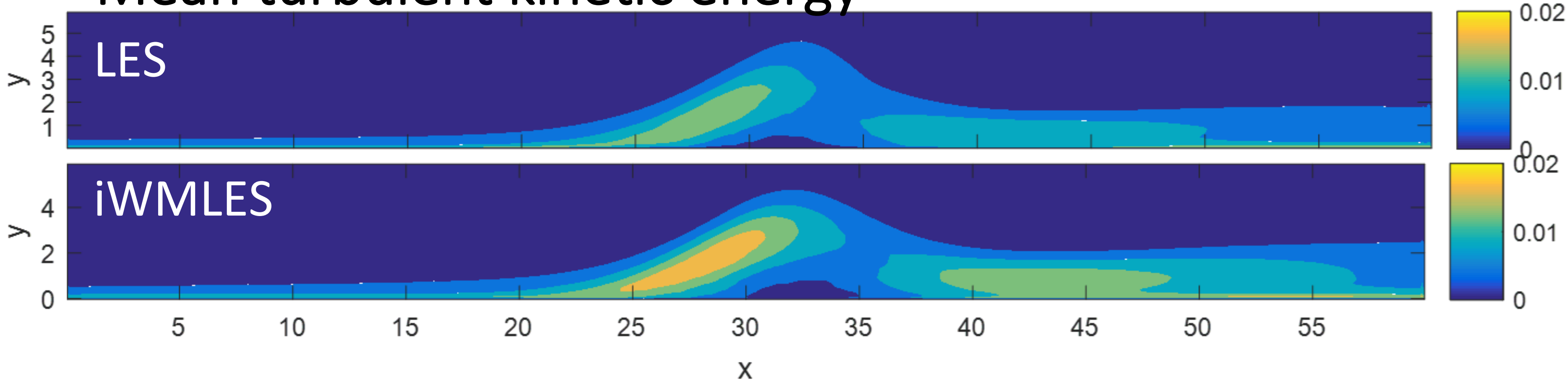


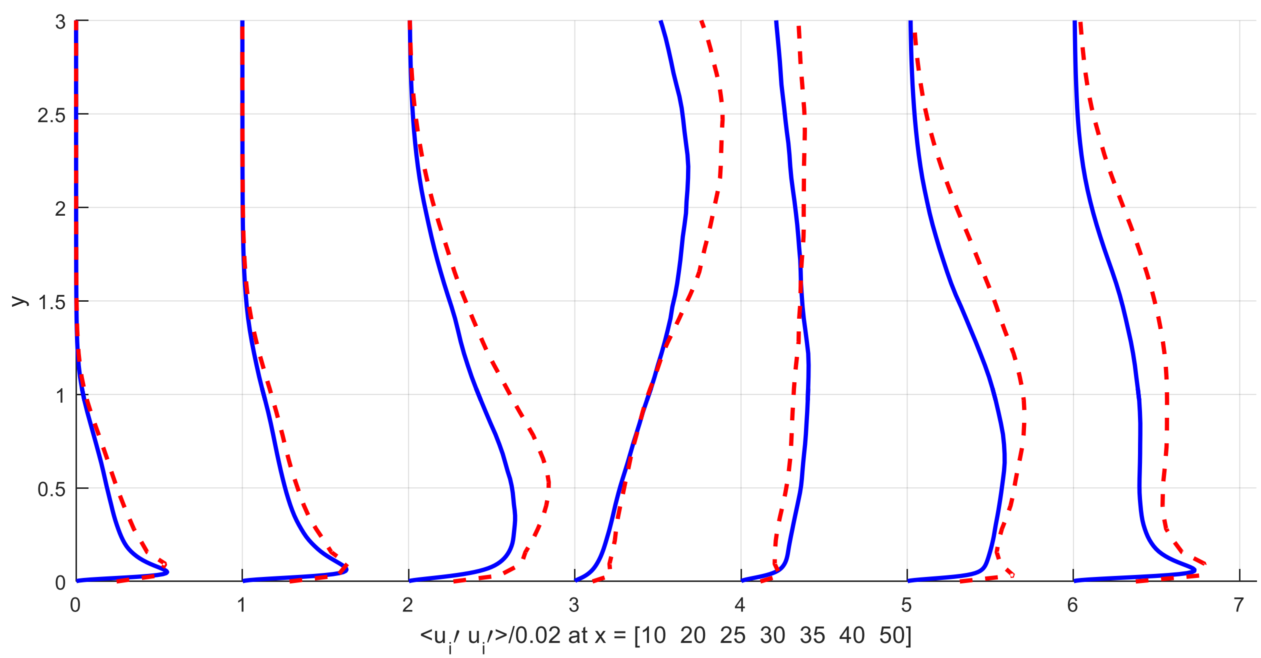


LES (lines)
iWMLES (dashes)

Results: iWMLES vs Wall-resolved LES

Mean turbulent kinetic energy

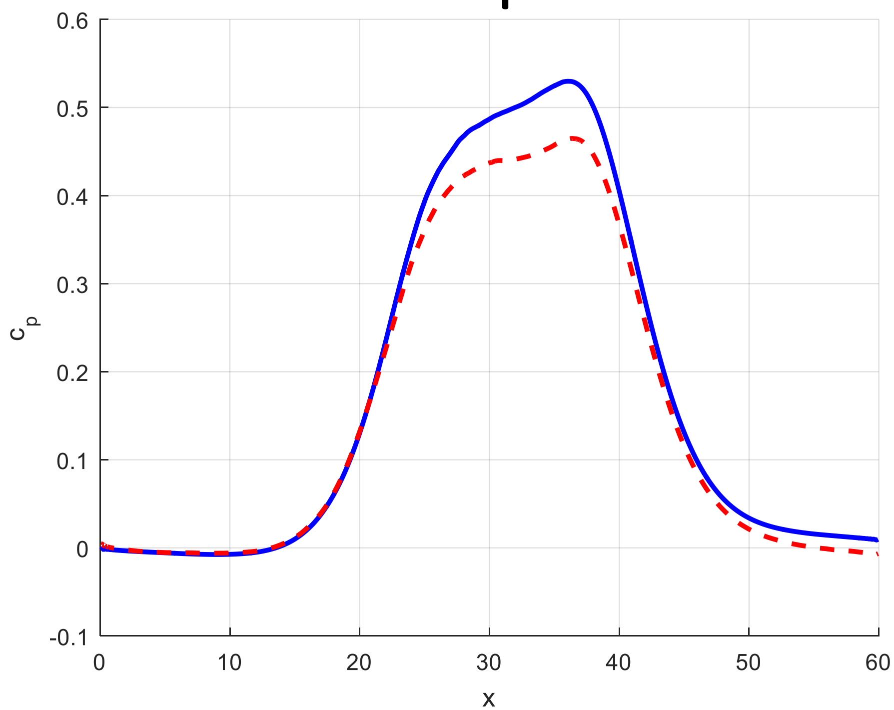




LES (lines)
iWMLES (dashes)

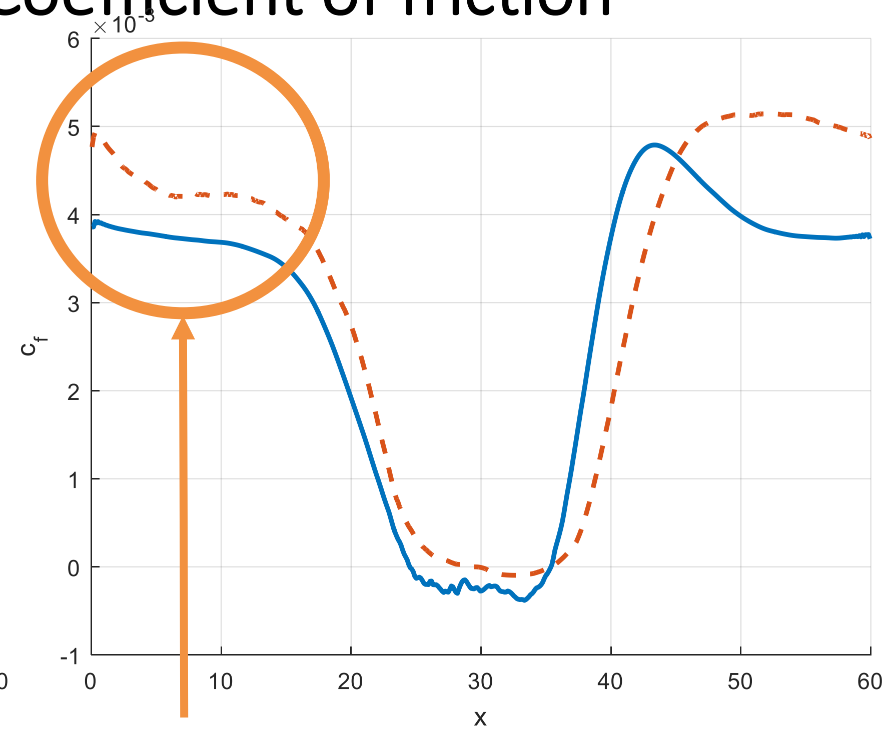
Results: iWMLES vs Wall-resolved LES

Coefficient of pressure



Wall-resolved LES (lines), iWMLES (dashes)

Coefficient of friction



Inlet friction velocity mismatch: effective Reynolds number from recycle-rescale method (*Lund et al*) in wall-resolved LES is higher than iWMLES

Conclusions

- Proposed a low-cost non-equilibrium integral Wall Model for LES (iWMLES)
- Validated iWMLES for canonical turbulent BL
- Demonstrated iWMLES capability to predict separation, and reattachment for a turbulent separation bubble flow → compared favorably with DNS despite inflow mismatch
- Showed preliminary, but promising comparison of iWMLES to wall-resolved LES for a turbulent separating and reattaching boundary layer

Outlook

- Ongoing: validation of turbulent recirculation zone over flat plate
  - Address inflow mismatch problem
- Next: perform validation for turbulent flow over airfoil against experimental data
- Future: use iWMLES to investigate active flow control to reattach flow over wing-flap or tail-rudder at operating Reynolds number

Thank You

Questions?

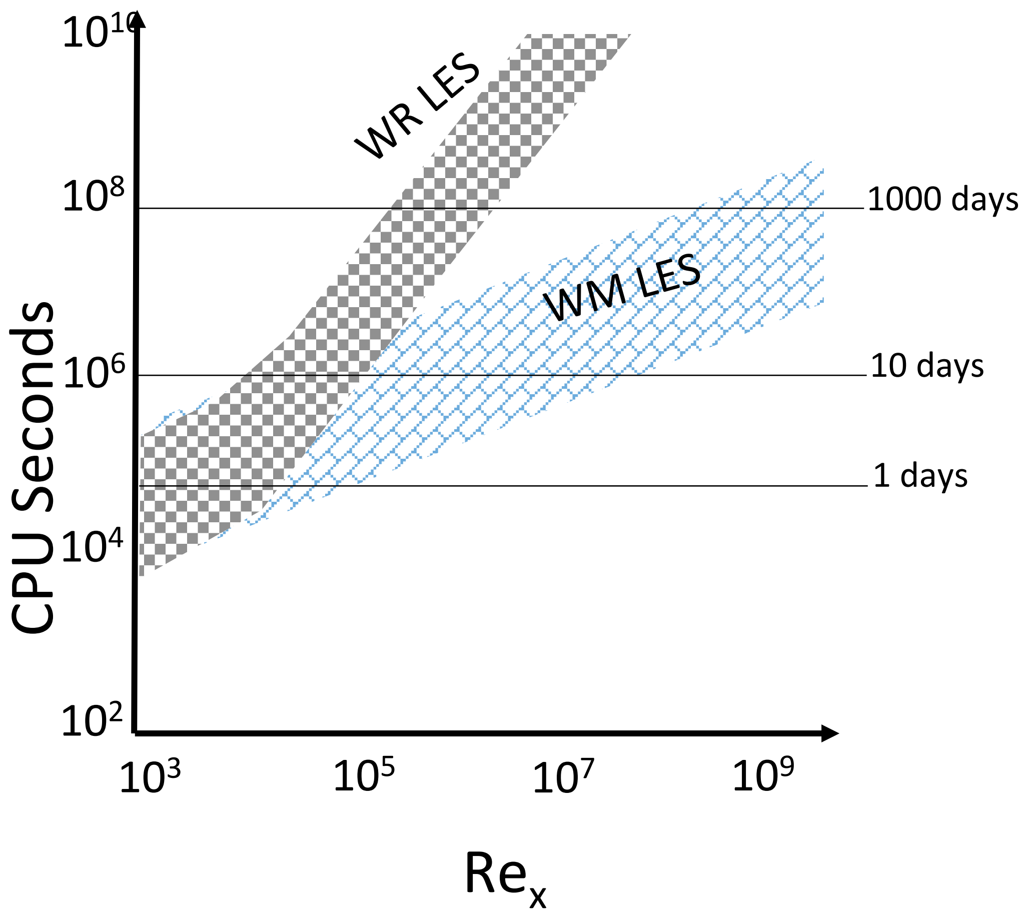
Know someone who might be interested in continuing this work?

Please let them know that Rajat Mittal (mittal@jhu.edu) & Charles Meneveau (meneveau@jhu.edu) are looking for a ***postdoc***

Acknowledgments

Research supported by AFOSR
under Grant FA9550-14-1-0289

Why Wall-Modeled LES?



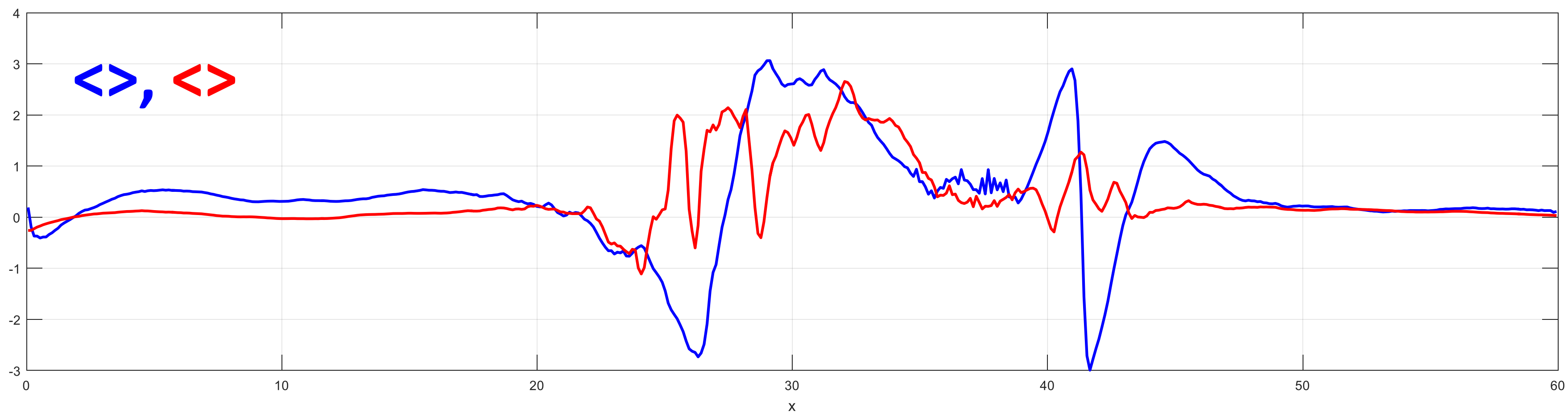
Piomelli, U. (2008), "Wall-layer models for large-eddy simulations", *Progress in Aerospace Sciences* **44**, 437.

Wall-resolved LES:

- Can capture mean flow, Cp, Cf, and Reynolds stress accurately at resolutions on the order of 1% of DNS
- Largely insensitive to choice of subgrid-scale model
- # of points resolve viscous sublayer:
- For $Re > 10^5$, >90% of grid points are used in <10% of the simulation domain (near boundaries)

Results: iWMLES vs wall-resolved LES

iWMLES Influence of non-equilibrium terms



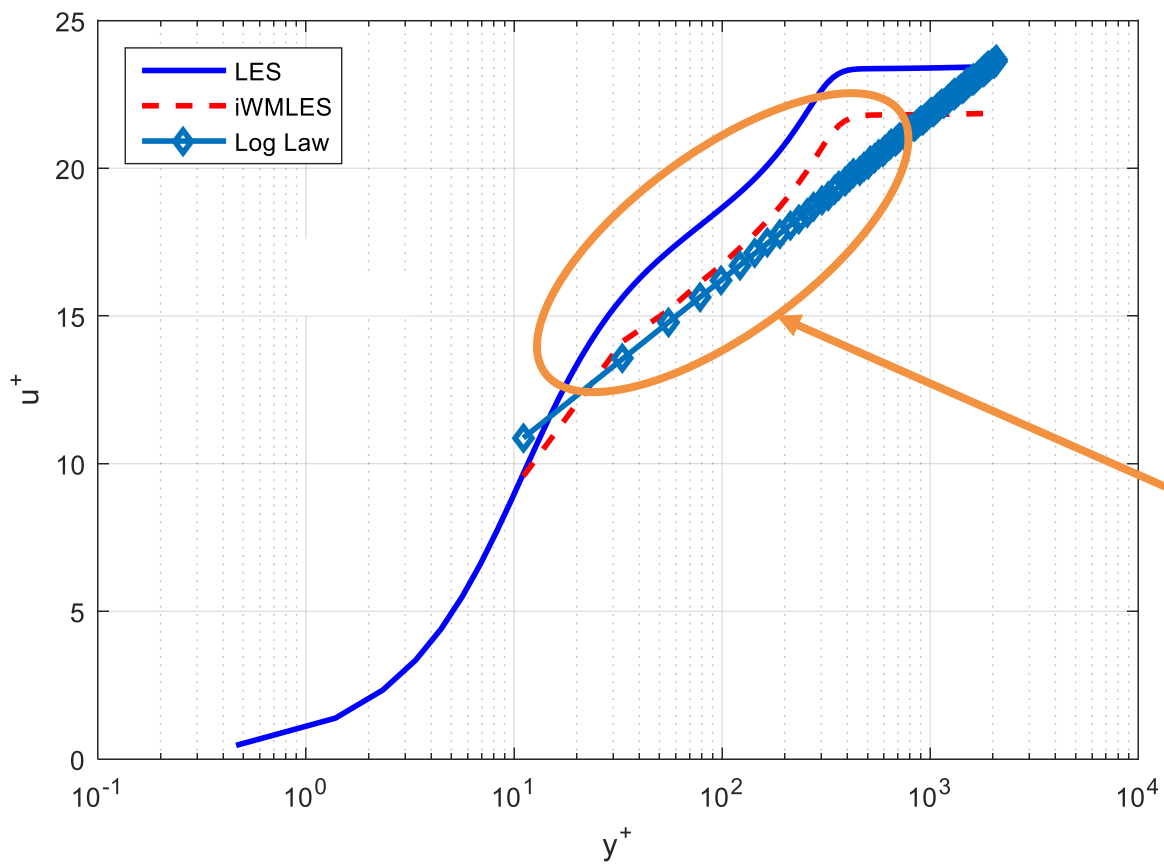
$$u = u_\nu \left[\frac{y}{\delta_\nu} \right]$$

$$u = u_\tau \left[C + \frac{1}{\kappa} \log\left(\frac{y}{\Delta_y} \right) + \boxed{A_2} \frac{y}{\Delta_y} \right]$$

Results: iWMLES vs Wall-resolved LES

Wall-resolved LES (lines) vs iWMLES (dashes)

$\Delta y^{+} \sim 1$ $\Delta y^{+} \sim 16,\ \Delta y^{+} \sim 100$



Wall-resolved LES disagrees with log-law at ‘inflow’ could be an indication of issues with recycle-rescale method

Why not RANS or Hybrid RANS-LES?

RANS limitations:

- Length/intensity of recirculation strongly depends on turbulence model
- requires resolving inner viscous layer ($y^{+} \leq 1$)

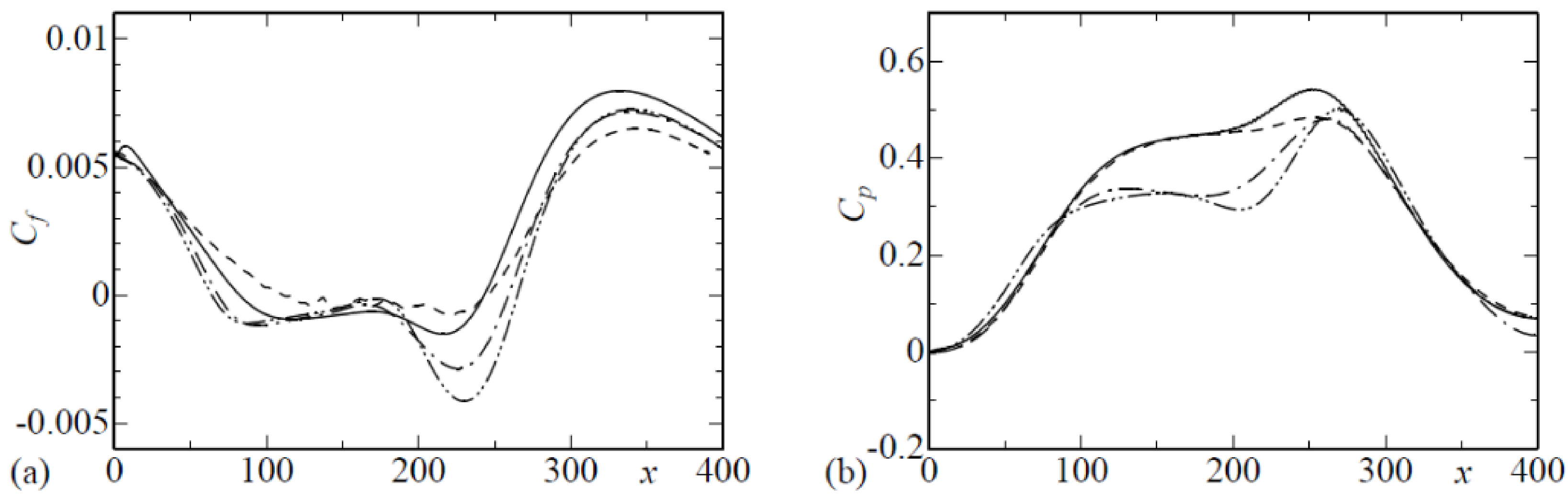


FIGURE 9. Model performance for C_f and C_p at $Re_\theta = 300$: (a) C_f ; (b) C_p. – – –, DNS; ——, k-ε; – · – · –, k-ω; – ·· – ·· –, SST.

Abe, H., Mizobuchi, Y., Matsuo, Y., & Spalart, P. (2012). DNS and modeling of a turbulent boundary layer with separation and reattachment over a range of Reynolds numbers. *Center for Turbulence Research Annual Research Briefs*, *143*.

Why Wall-Modeled LES?

Estimates for Canonical Turbulent Boundary Layer

	Re_x=10^6	Re_x=10^7
Wall Resolved LES	8.7x10^7	1.4x10^{10}
Hybrid RANS-LES	1.4x10^7	2.0x10^7
Integral Wall Model LES*	3.0x10^6	3.0x10^6

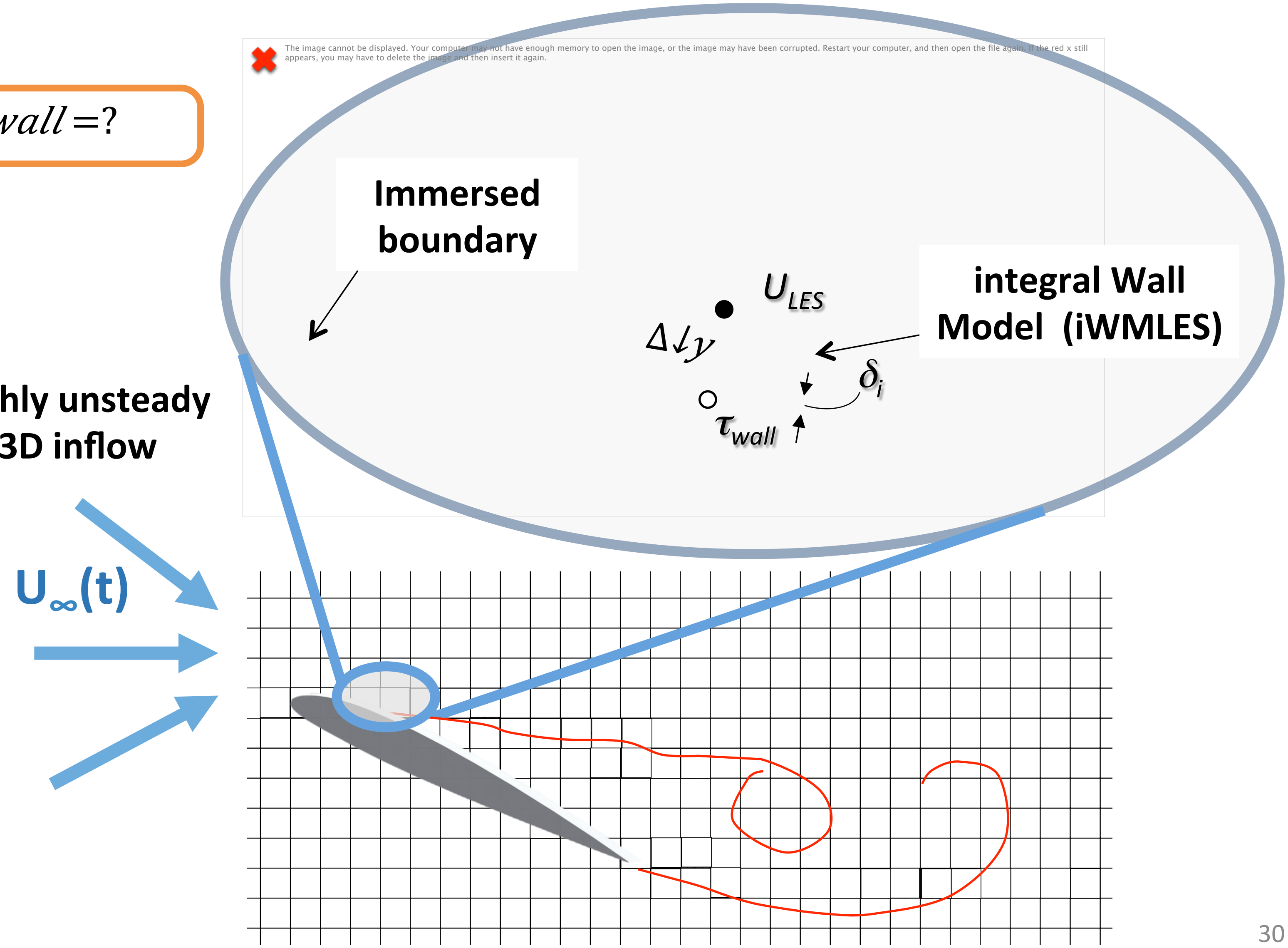
Estimated # of grid points in the boundary layer region for different methods and Reynolds numbers.

*Yang, X.I.A., Sadique, J., Mittal, R. & Meneveau, C. (2015), "Integral Wall Model for Large Eddy Simulations of wall-bounded turbulent flows". *Phys. Fluids* **27**, 025112.

What is wall-modeled LES?

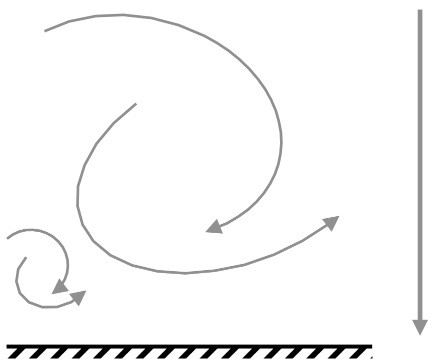
$\boxed{\tau\downarrow wall = ?}$

Highly unsteady 3D inflow



Integral Wall Model (iWMLES)

Filter velocities in time to match near wall time scale



$$\langle u_i \rangle = \int_{-\infty}^{t} u_i(x,y,z,t') \frac{1}{T_{wall}} e^{-(t-t')/T_{wall}}$$

$$U_{LES} = \int_{-\infty}^{t} u(x,y=\Delta_y,z,t') \frac{1}{T_{wall}} e^{-(t-t')/T_{\nu}}$$

where $T_{wall} = \Delta_y / \kappa u_\tau$

→ Obtain RANS like equations for $\langle u_i \rangle$ with $\nu_\tau = l_m |\partial\langle U\rangle/\partial y|$

→ Vertically integrate equations from 0 to Δ_y

→ Solve for τ_w using a parametric velocity profile

LES Wall-modeling approaches

	Equilibrium	Zonal/Hybrid	Dynamic Slip	Integral WM
Solves	Equilibrium TBL (log law)	Full RANS	ODE for slip velocity	Vertically Integrated Momentum
Strength	Simple	Wealth of experience	Simple	Versatile
Weaknesses	Needs correction for laminar/ transitional flow	Requires embedded grid and RANS solver	Grid dependence, slip is not physical	Assumed profile may not be valid for all flows
CPU Cost	Negligible	High	Low	Very Low

Results: Turbulent Separation Bubble

Reynolds stress <u'v'>

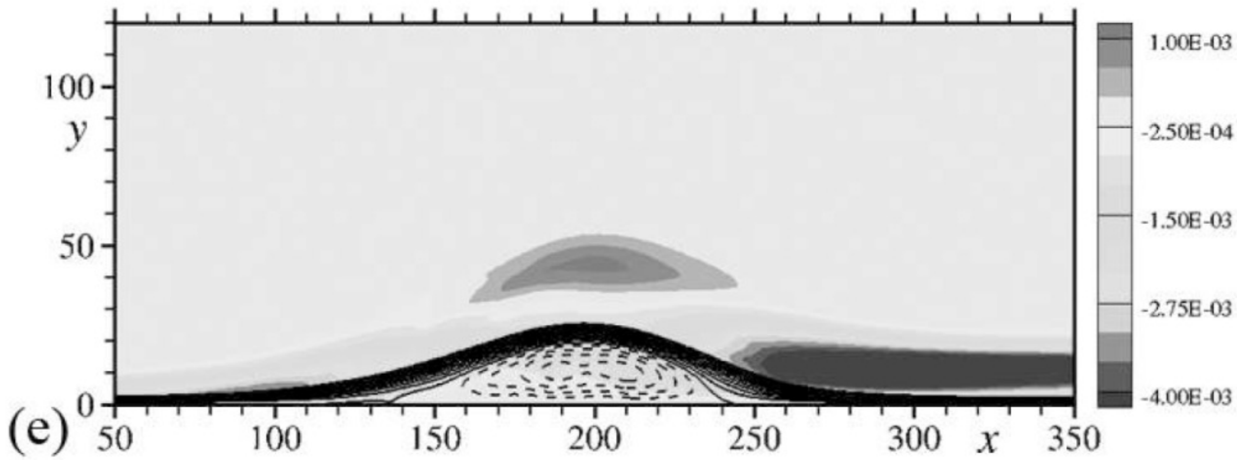
DNS*

$Re_{\theta_0} = 300$

$\Delta x_0^+ = 7.92$

$\Delta y_0^+ = 0.11$

$\Delta z_0^+ = 4.22$



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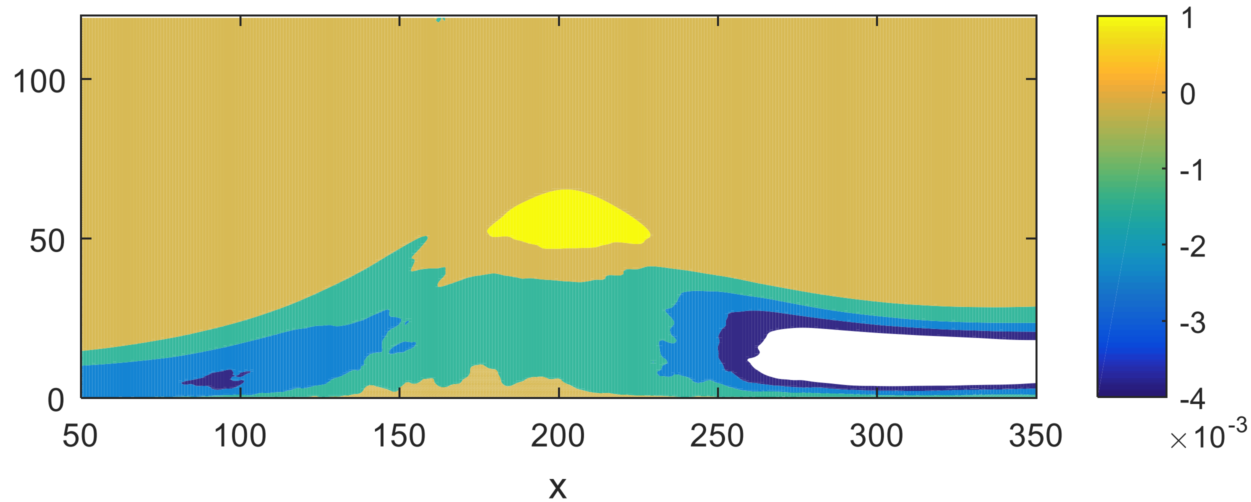

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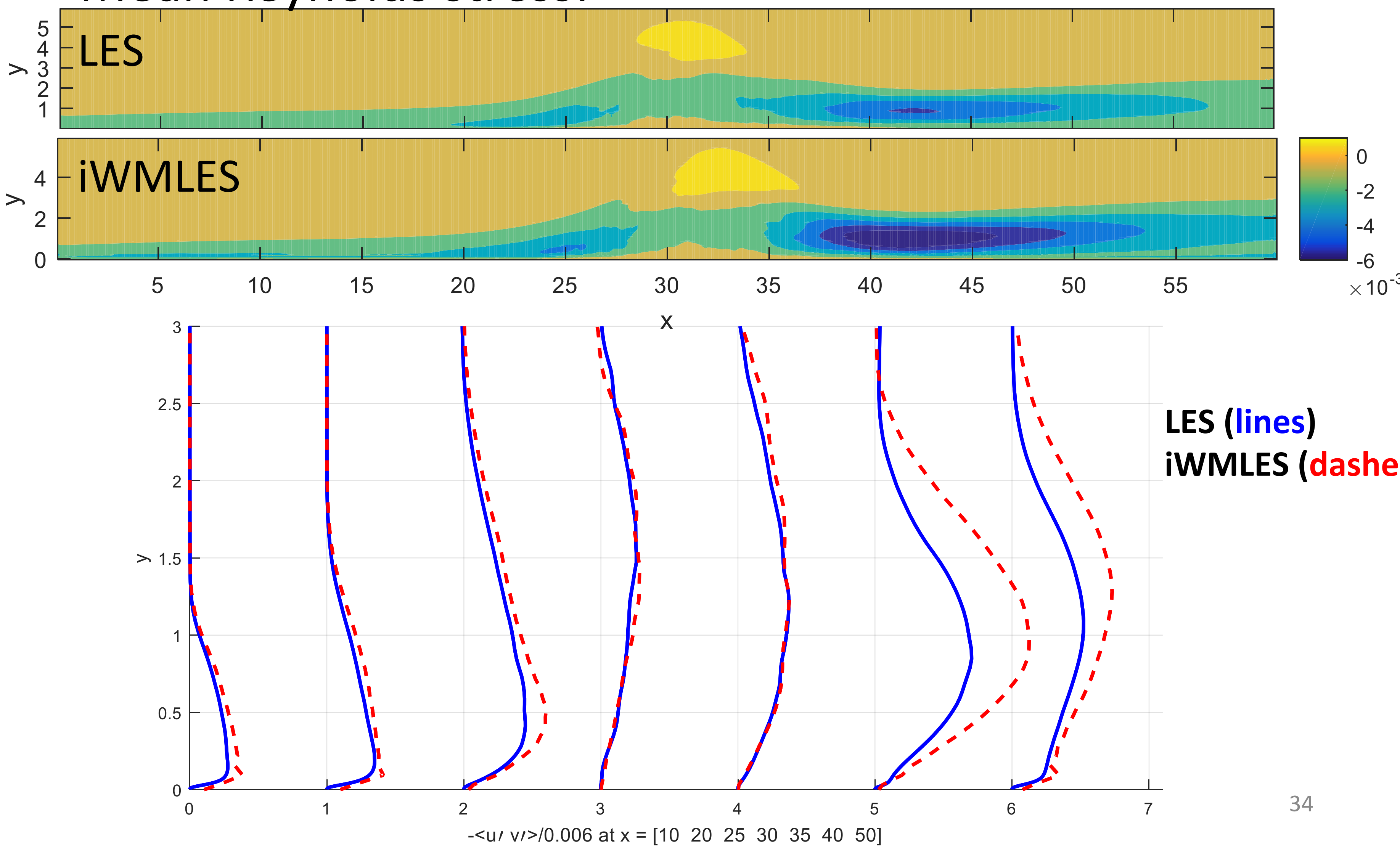
Results: iWMLES vs Wall-resolved LES

Mean Reynolds stress:



LES (lines)
iWMLES (dashes)